

**Fermilab**  
ES&H Section

E. P. Note No. 11

**CONTRIBUTION OF NEUTRON SKYSHINE TO OFF-SITE DOSES**

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March 1996

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#### Introduction

Skyshine, or radiation scattered back to ground level, is a well-known phenomenon sometimes found at high-energy particle accelerators and also at other radiological facilities containing highly radioactive materials. If the roof of the enclosure does not contain a sufficient amount of shielding, radiation may leak through the structure and then be scattered back at various angles to ground level possibly resulting in significant dose equivalents at distant locations.

In general, the contribution by neutron skyshine to radiation doses received by members of the public resulting from Fermilab operations is inconsequential. Extensive efforts have been made to ensure that adequate shielding is maintained throughout the accelerator facilities. However, under accidental conditions or conditions in which a large area was poorly shielded, it may be possible to generate a source of sufficient strength that would yield measurable doses from skyshine. This paper summarizes the calculations performed to allow an individual to estimate the dose to a member of the public due to neutron skyshine.

#### Calculational Methods

Two different methods, described below, were used to obtain values for the dose equivalent rate at a given distance from a source attributable to neutron skyshine. The calculations were performed using Microsoft Excel 4.0<sup>TM</sup> and the resulting spreadsheets are included as appendices to this paper.

Four variables were incorporated into the tables: source strength expressed as an average dose equivalent rate over source area; source area; maximum energy of the neutrons being emitted in an assumed 1/E spectrum; and distance from the source. Since all combinations of these variables could not be anticipated, it should be noted that the dose equivalent rate will scale linearly with both the source strength and the source area and for approximation purposes, inversely with the square of the distance from the source at distances in excess of about 100 m. For reference, the values on which the spreadsheet calculations were based are provided below.

##### Source Strength (mrem/hr)

100, 250, 500, 1000, 2500, 5000, 10000

##### Maximum energy of neutrons being emitted (MeV)

1.6, 2.5, 4.0, 6.3, 10, 16, 25, 40, 63, 100, 160, 250,  
400, 630, 1000, 1600, 2500, 4000, 6300, 10000

##### Source Area (ft<sup>2</sup>)

1, 25, 100, 625, 2500, 10000

##### Distances from the Source (m)

50, 100, 250, 500, 750, 1000

Several assumptions were made in these calculations. The first assumption was that neutrons only contributed 90% of the measured dose equivalent. The remaining 10% was assumed to be from

photons. This would be a typical fractionation of the dose equivalent as measured by a standard ion chamber survey instrument. The portion attributed to photons is explicitly ignored in the skyshine calculations. The second assumption was that the neutron energy spectrum has an energy dependence that is well-represented by the function 1/E. By making this assumption, the effective absorption lengths  $\lambda$  as determined by Stevenson and Thomas [1984] could be used. It was also assumed that the radiation field generated by the neutrons was uniform throughout the source area.

The first spreadsheet, Neutron Skyshine--Method 1, applies the empirical equation derived by Patterson and Thomas [1973] which is valid for distances greater than 50 m:

$$[1] \quad \phi(r) = \frac{aQ}{4\pi r^2} (1 - e^{-r/\mu}) e^{-r/\lambda}$$

where  
 $a$  = buildup factor  
 $\mu$  = buildup relaxation length  
 $r$  = distance from the source (m)  
 $\lambda$  = effective interaction length (m)  
 $Q$  = source strength

Taking the values of  $a$  and  $\mu$  of 2.8 and 56 m respectively as given in Cossairt [1995], Equation [1] simplifies to:

$$[2] \quad \phi(r) = \frac{0.223Q}{r^2} (1 - e^{-r/56\text{ m}}) e^{-r/\lambda}$$

Values for  $\lambda$  are based upon the upper, or maximum, energy of the 1/E spectrum [Stevenson and Thomas 1984]. Thus, to use the spreadsheet, the maximum neutron energy is required. The upper energy can be taken from measurements of the neutron energy spectrum, determined from shielding calculations, or inferred from the nature of the shield when compared with similar shields where more detailed spectral information is available. The spreadsheet takes into consideration the dose equivalent rate of the source and the source area to calculate  $Q$  in units of rem  $\text{m}^2 \text{ hr}^{-1}$ . It then, using appropriate values for  $\lambda$ , calculates the corresponding dose equivalent as a function of the distance from the source.

The other spreadsheet, Neutron Skyshine--Method 2, utilizes the empirical results of Sullivan [1992], valid for distances from the source of greater than 100m. Stevenson and Thomas [1984] arrived at a similar conclusion. Differences between the two equations are due to unit conversions and the inclusion of the time dimension by Sullivan.

$$[3] \quad H(r) = \frac{10^{-9} e^{-r/\lambda}}{r^2} \frac{\text{rem hr}^{-1}}{\text{neutrons s}^{-1}}$$

where  
 $r$  = distance from the source (m)  
 $\lambda$  = effective interaction length (m)

The values for  $\lambda$  are the same as those used in Method 1. This spreadsheet calculates a value for the source strength S in units of neutrons per second taking into consideration the energy dependence of the dose equivalent to fluence conversion, the dose equivalent rate of the source and the source area.

$$[4] \quad S = \frac{\dot{H}_s * A}{K(E) * 3600} \quad \frac{\text{neutrons}}{\text{s}}$$

where  $\dot{H}_s$  = neutron dose equivalent rate of the source (rem/hr)

A = source area ( $\text{cm}^2$ )

K(E) = spectrum averaged dose equivalent conversion (rem/n  $\text{cm}^{-2}$ )

Appropriate values for K(E) are tabulated in Stevenson and Thomas [1984]. Multiplying the values of S by the values for H(r), one obtains the dose equivalent rate at a given distance from the skyshine source.

The spreadsheet entitled Neutron Skyshine--Method 1 is incorporated into Appendix A in its entirety. Appendix B contains the Neutron Skyshine--Method 2 spreadsheet. Figures 1-3 graphically display values of dose equivalent multiplied by the square of the distance as a function of distance from the source obtained from both the spreadsheets for comparison between the two calculational methods and for quick reference. Figures 1 and 2 illustrate the linear scaling between values for source strength and also for source area. Figure 3 demonstrates the dependence upon the maximum neutron energy. Note that Method 1 does not directly depend on the number of neutrons leaking through the shield, whereas Method 2 does. This explains the decrease in dose equivalent seen in Method 2 at higher neutron energies with all other variables kept constant; the number of neutrons emitted by the source per unit dose equivalent decreased as a function of maximum energy. The number of neutrons scattered back to ground level may be affected by other physical processes such as showering at high neutron energies ( $> 10 \text{ GeV}$ ), which are not accounted for in these spreadsheets.

### Discussion and Conclusions

The two computational methods do yield slightly different results for the same conditions as exhibited in Figures 1 - 3. Keeping in mind that both methods are based on equations derived from empirical fits to collected data and that a true  $1/E$  spectrum would not exist under these conditions, the agreement between the two computational methods and experimental results is quite good at distances greater than 100 m from the source. It is recommended that Method 1 be utilized to extrapolate doses that might be received by individuals as it takes into account the buildup with distance that is seen in experimental results [Stevenson and Thomas 1984] and it relies on the dose equivalent averaged over the source area rather than the number of neutrons leaking through the shield.

These spreadsheets provide a relatively easy way of accounting for the contribution of neutron skyshine upon off-site external doses. If the source area can be measured, the dose equivalent rate estimated and the upper neutron energy approximated, the dose equivalent rate as a function of distance away from the source can be determined. When combined with dose equivalents received from other sources, such as airborne emissions and muons, it can be used to demonstrate compliance with applicable regulations and requirements.

### Acknowledgments

The author would like to Kamran Vaziri and Don Cossairt for their patient review of the spreadsheets that comprised this work.

## References

- J. D. Cossairt. *Topics in Radiation at Accelerators: Radiation Physics for Personnel and Environmental Protection.* FERMILAB-TM-1834. Fermi National Accelerator Laboratory. June 1995.
- H. W. Patterson and R. H. Thomas. *Accelerator Health Physics.* New York: Academic Press, 1973.
- G. R. Stevenson and R. H. Thomas, "A Simple procedure for the estimation of neutron skyshine from proton accelerators", *Health Physics*, 46 (1984) 115-122.
- A. H. Sullivan. *A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators.* Ashford, England: Nuclear Technology Publishing, 1992.

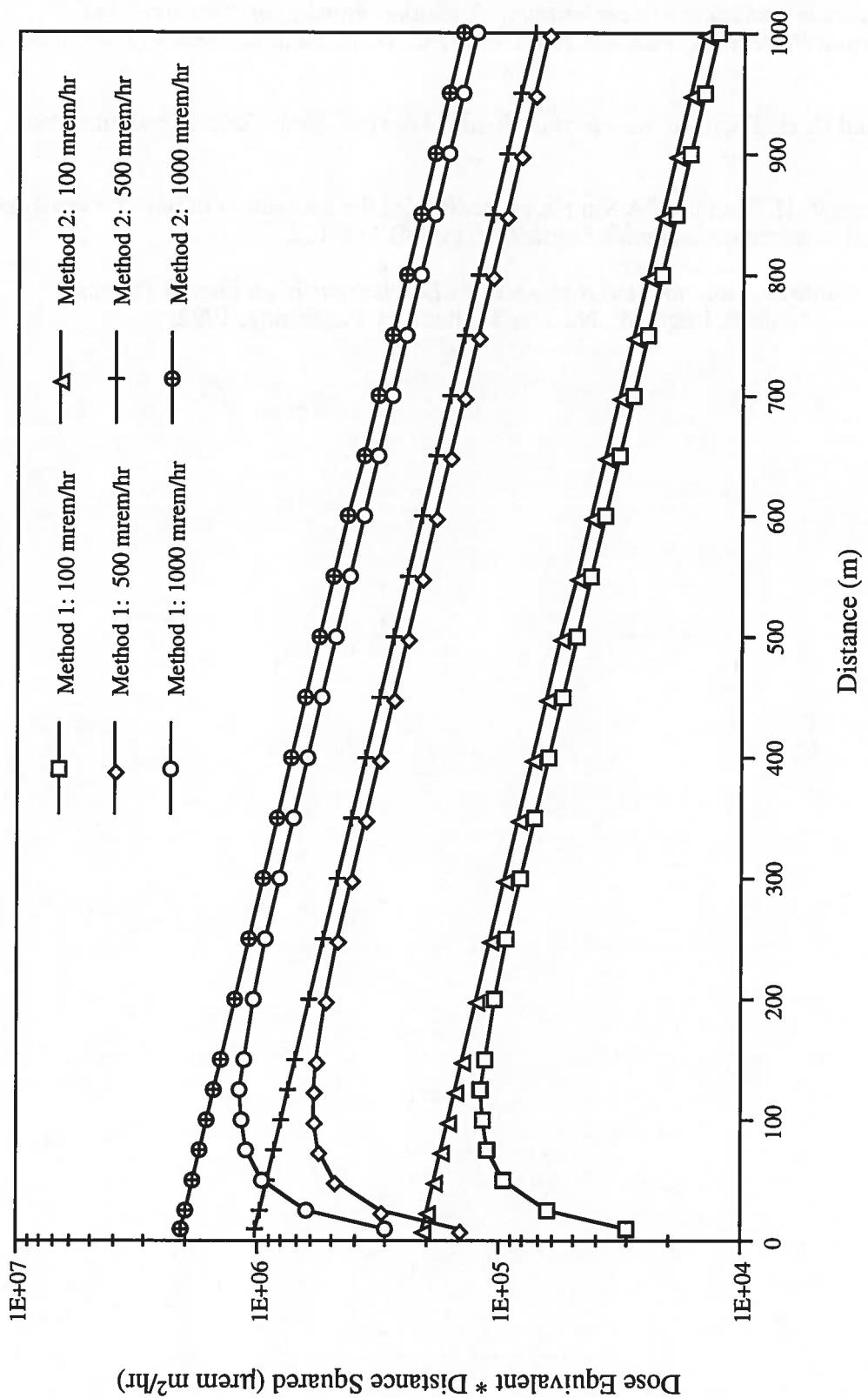


Figure 1: Comparison at 100 MeV maximum neutron energy and 100 ft<sup>2</sup> area.

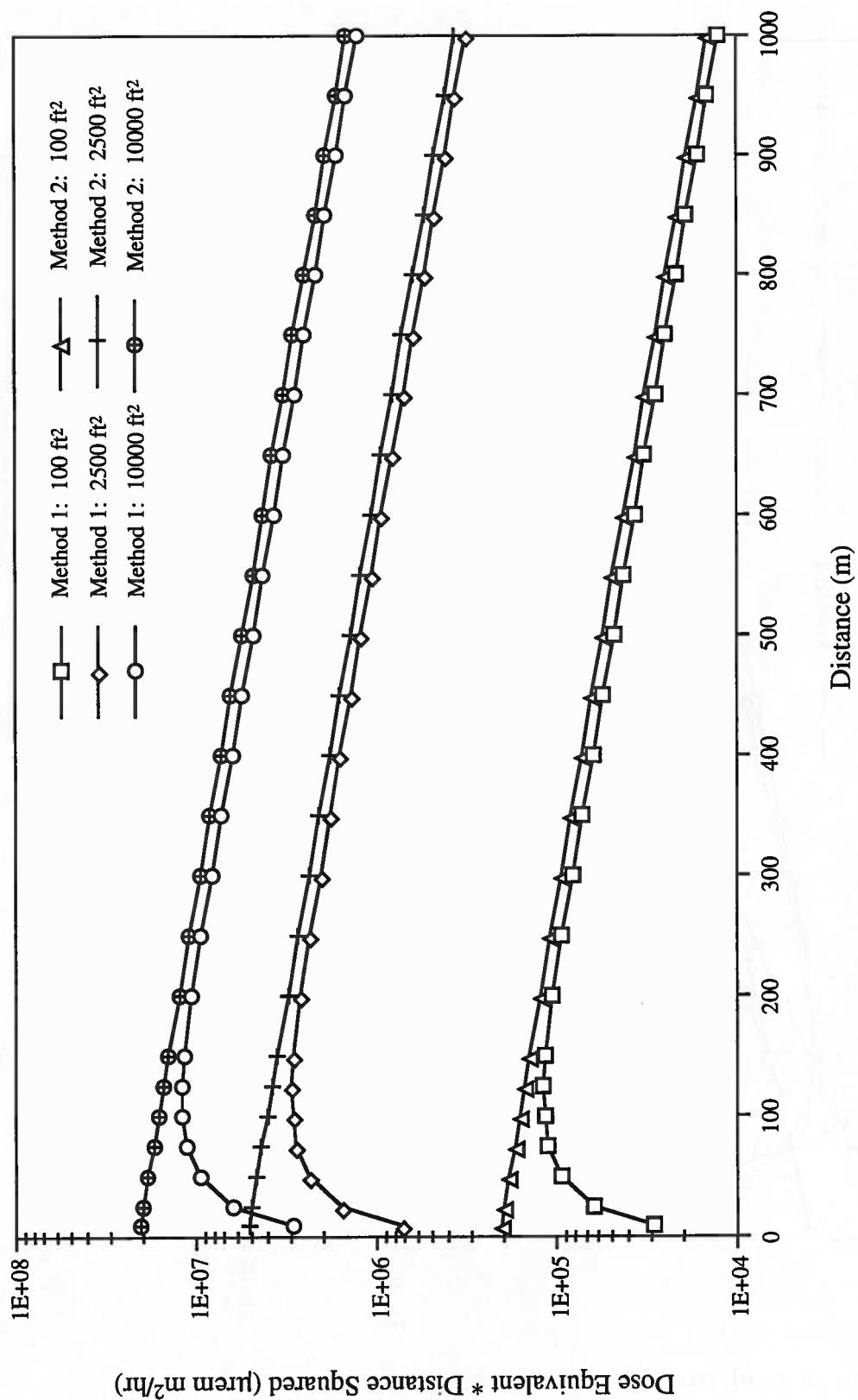
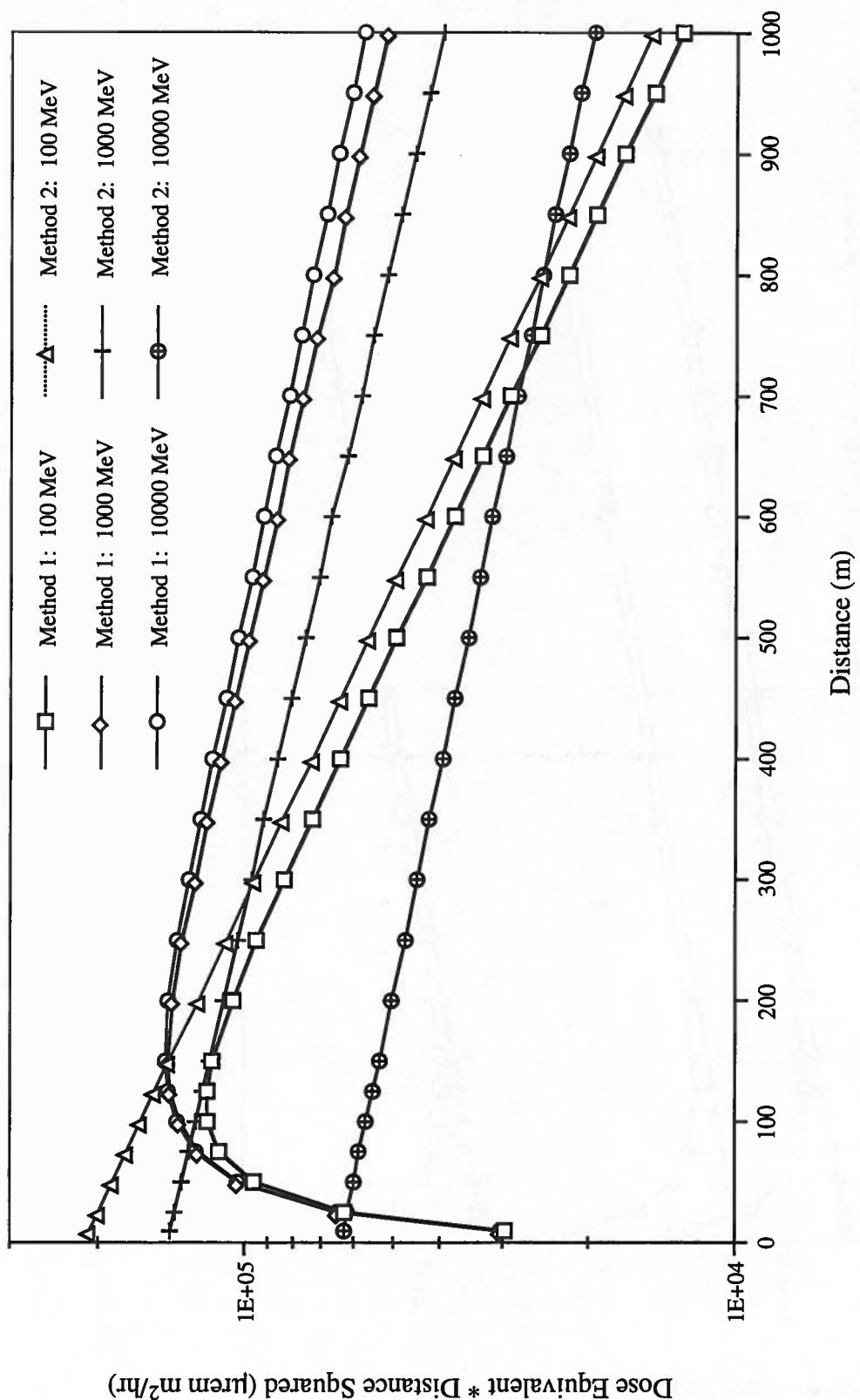


Figure 2: Comparison at 100 mrem/hr and 100 MeV maximum neutron energy.

Figure 3: Comparison at 100 mrem/hr and 100 ft<sup>2</sup> area.









Appendix A  
Neutron Skyshine-Methode 1

(1) Area=1 sq ft		9.29E-02	m^2	(4) Area=625 sq ft		5.81E+01	m^2						
(2) Area=25 sq ft		2.32E+00	m^2	(5) Area=2500 sq ft		2.32E+02	m^2						
(3) Area=100 sq ft		9.29E+00	m^2	(6) Area=10000 sq ft		9.29E+02	m^2						
Dose Equivalent Rate (rem/hr)	Neutron Dose Equivalent (rem/hr)	Unit Conversion (rem/hr)	Upper Neutron Energy (MeV)	Q (rem m2/hr) for Area 1	Q (rem m2/hr) for Area 2	Q (rem m2/hr) for Area 3	Q (rem m2/hr) for Area 4	Q (rem m2/hr) for Area 5	Q (rem m2/hr) for Area 6	Lambda			
500	450	4.50E-01	1.6	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	165			
500	450	4.50E-01	2.5	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	175			
500	450	4.50E-01	4	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	180			
500	450	4.50E-01	6.3	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	200			
500	450	4.50E-01	10	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	220			
500	450	4.50E-01	16	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	235			
500	450	4.50E-01	25	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	250			
500	450	4.50E-01	40	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	275			
500	450	4.50E-01	63	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	315			
500	450	4.50E-01	100	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	375			
500	450	4.50E-01	160	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	425			
500	450	4.50E-01	250	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	500			
500	450	4.50E-01	400	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	610			
500	450	4.50E-01	630	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	700			
500	450	4.50E-01	1000	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	780			
500	450	4.50E-01	1600	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	820			
500	450	4.50E-01	2500	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	835			
500	450	4.50E-01	4000	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	850			
500	450	4.50E-01	6300	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	850			
500	450	4.50E-01	10000	4.18E-02	1.05E+00	4.18E+00	2.61E+01	1.05E+02	4.18E+02	850			



















Appendix B  
Neutron Skyshine—Method 2

Distance (m)	H ( $\text{Sv}/\text{h}/(\text{n}/\text{s})$ )	Dose Equivalent Area (1) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (2) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (3) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (4) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (5) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (6) ( $\mu\text{rem}/\text{hr}$ )	Distance (m)	H ( $\text{Sv}/\text{h}/(\text{n}/\text{s})$ )	Dose Equivalent Area (1) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (2) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (3) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (4) ( $\mu\text{rem}/\text{hr}$ )	Dose Equivalent Area (5) ( $\mu\text{rem}/\text{hr}$ )	
250	3.52E-17	2.09E-02	5.24E-01	2.09E+00	1.31E+01	5.24E+01	2.09E+02	500	1.93E-18	1.15E-03	2.88E-02	1.15E-01	7.19E-01	2.88E+00	1.15E+01
250	3.83E-17	1.86E-02	4.64E-01	1.86E+00	1.16E+01	4.64E+01	1.86E+02	500	2.30E-18	1.11E-03	2.78E-02	1.11E-01	6.95E-01	2.78E+00	1.11E+01
250	3.99E-17	4.14E-02	1.03E+00	4.14E+01	1.03E+02	4.14E-02	500	3.28E-18	2.98E-03	7.45E-02	2.98E-01	1.86E+00	7.45E+00	2.98E+01	
250	4.58E-17	4.16E-02	1.04E+00	4.16E+01	2.60E+01	1.04E+02	4.16E+02	500	4.12E-18	3.32E-03	8.31E-02	3.32E-01	2.08E+00	8.31E+00	3.32E+01
250	5.14E-17	4.14E-02	1.04E+00	4.14E+01	2.59E+01	1.04E+02	4.14E+02	500	4.76E-18	3.50E-03	8.75E-02	3.50E-01	2.19E+00	8.75E+00	3.50E+01
250	5.52E-17	4.06E-02	1.01E+00	4.06E+00	2.54E+01	1.01E+02	4.06E+02	500	5.41E-18	3.65E-03	9.14E-02	3.65E-01	2.28E+00	9.14E+00	3.65E+01
250	5.89E-17	3.97E-02	9.94E-01	3.97E+00	2.48E+01	9.94E+01	3.97E+02	500	6.49E-18	4.01E-03	1.00E-01	4.01E+01	2.51E+00	1.00E+01	4.01E+01
250	6.45E-17	3.59E-02	4.51E-01	3.59E+00	1.80E+01	4.51E+01	3.59E+02	500	1.47E-17	2.73E-03	6.84E-02	2.73E-01	1.71E+00	6.84E+00	2.73E+01
250	7.24E-17	1.66E-02	4.16E+01	1.66E+00	1.04E+01	4.16E+01	1.66E+02	500	8.18E-18	1.88E-03	4.70E-02	1.88E-01	4.70E+00	1.88E+01	4.70E+01
250	7.24E-17	1.66E-02	4.16E+01	1.66E+00	1.04E+01	4.16E+01	1.66E+02	500	1.05E-17	2.25E-03	5.62E-02	2.25E-01	1.40E+00	5.62E+00	2.25E+01
250	8.21E-17	1.78E-02	4.45E-01	1.78E+00	1.11E+01	4.45E+01	1.78E+02	500	1.96E-17	3.12E-03	7.79E-02	3.12E-01	1.95E+00	7.79E+00	3.12E+01
250	1.16E-16	1.60E-02	4.41E-01	1.60E+00	1.04E+01	4.16E+01	1.60E+02	500	2.11E-17	3.02E-03	7.55E-02	3.02E-01	1.89E+00	7.55E+00	3.02E+01
250	1.18E-16	3.72E-02	9.31E-01	3.72E+00	9.31E+01	3.72E+02	9.31E+00	500	2.17E-17	6.86E-03	1.72E-01	6.86E-01	4.29E+00	1.72E+01	6.86E+01
250	1.19E-16	8.12E-01	3.25E+01	8.12E+01	3.25E+02	8.12E+01	3.25E+02	500	2.20E-17	6.02E-03	1.50E-01	6.02E-01	3.76E+00	1.50E+01	6.02E+01
250	1.19E-16	2.77E-02	6.92E-01	2.77E+00	6.92E+01	2.77E+02	6.92E+00	500	2.22E-17	5.16E-03	1.29E-01	5.16E-01	3.22E+00	1.29E+01	5.16E+01
250	1.19E-16	2.31E-02	5.77E-01	2.31E+00	2.31E+01	5.77E+00	2.31E+01	500	2.22E-17	4.30E-03	2.31E-01	4.30E-01	2.69E+00	1.07E+01	4.30E+01
250	1.19E-16	1.90E-02	4.74E-01	1.90E+00	1.19E+01	4.74E+01	1.90E+02	500	2.22E-17	3.53E-03	8.83E-02	3.53E-01	2.21E+00	8.83E+00	3.53E+01

















